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Thermal and hydrodynamic analysis of microchannel heat sinks: A review

Ahmed Mohammed Adham [a,*], Normah Mohd-Ghazali [a], Robiah Ahmad [b]

[a] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia
[b] UTM Razak School of Engineering and Advanced Technology, Universiti Teknologi Malaysia International Campus, 54100 Jalan Semarak, Kuala Lumpur, Malaysia

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ABSTRACT

An impressive amount of investigation has been devoted to enhancing overall thermal and hydrodynamic performance of microchannel heat sinks. The small size of microchannel heat sinks and their ability to dissipate heat generated by modern electronics makes them the first choice for the electronic cooling systems in most devices. In this paper, a comprehensive review of available studies regarding non-circular microchannel heat sinks, with emphasis on rectangular microchannels, was presented and analyzed. This review looked into the methodologies used to analyze and optimize the overall performance of microchannel systems along with channel geometries, flow conditions, the coolants used, structural materials, optimization tools and finally, the form in which the final outcome of each study was presented. The review showed that earlier studies (from 1981 to 1999) were largely conducted using experimental or analytical approaches while more recent studies (from 2000 to the end of 2012) showed a dependency on numerical simulations and evolutionary algorithms. In addition, they also showed that laminar was the prevailing flow condition as out of the 69 articles reviewed, 54 employed laminar flows. Furthermore, the use of liquid coolants was preferable over gaseous coolants. Recent developments in nanofluids are providing alternative coolants that are quickly establishing as coolants to be reckoned with.

Contents

1. Introduction

For decades, the successful use of microelectronic mechanical systems (MEMS) in electronic cooling applications made them the ultimate choice for thermal management control engineers. Improving the performance of MEMS to equalize the drastic increase in the

* Corresponding author. Tel.: +60 123398728; fax: +60 326934844.
E-mail addresses: ahamedadhm@yahoo.com, ahamedadhm@gmail.com (A. Mohammed Adham).

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rate of the heat generated by the modern electronic chips remains an attractive subject for further research. One of the most feasible applications for MEMS is the microchannel heat sink. These consist of several attached microchannels with a covering plate, which is usually made of a low thermal conductive material (adiabatic) such us glass, to confine the flow of the coolant. As the coolant flows through the microchannels, it removes the heat generated by the electronic chip.

The landmark study by Tuckerman and Pease [1] was the first attempt to use a microchannel heat sink for electronic cooling. This opened the door for further investigations in that area. Since then, much effort has been devoted in improving the capabilities of microchannel heat sinks to remove the heat generated by electronic chips.

Improvements in the development of microchannel heat sinks include the use of different microchannel geometries such as circular, rectangular, triangular, and trapezoidal designs (see Fig. 1) to increase the area available for heat transfer. They also used different materials with high thermal conductivity such as copper, aluminum, and silicon (see Fig. 2) to make the microchannel heat sinks. A combination of two materials was also considered so that the attaching defects with the electronic chips could be exceeded.

The increase in the rate of the heat generated by increasingly powerful electronics that continued to decrease in size forced designers to search for alternative coolants with better heat removal capabilities better than the abilities provided by air. One alternative was liquid coolants (see Table 1). Liquid coolants, including water, have been used in electronics cooling because of their relatively high heat removal capabilities. Recently, developments in the nanoparticles fabrication processes has led to an increase in the studies pertaining to nanofluids in an attempt to find effective alternative coolants with better heat removal capabilities.

Gaseous and liquid coolants each have their advantages and disadvantages, which designers can use to select a suitable coolant for a particular application. Table 2 summarizes the advantages and disadvantages of the coolants currently used in the microchannel heat sink industry. As part of the attempts to

Table 1
Coolant types employed in the previous studies.

Authors	Years	Coolant used
Tuckerman and Pease [1]	1981	Water
Kleiner et al. [3]	1995	Air
Harley et al. [4]	1995	Nitrogen
		Helium
		Argon
Harms et al. [5]	1999	Deionized water
Kim and Kim [6]	1999	Water
Choi and Cho [7]	2001	Paraffin
		Water
Qu and Mudawar [8]	2002	Deionized water
Gamrat et al. [9]	2005	Water
Khan et al. [10]	2006	Air
Mohammed et al. [11]	2010	Alumina–water
Cho et al. [12]	2010	R-123
Moharana et al. [13]	2011	Deionized water
Escher et al. [14]	2011	SiO_2–water
Mohammed et al. [15]	2011	Diamond–water
		Diamond–EG
		Diamond–oil
		Diamond–glycerin

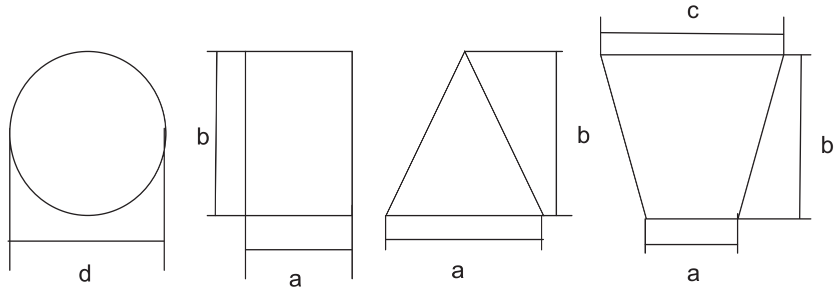

Fig. 1. Different microchannel geometries utilized in the previous studies.

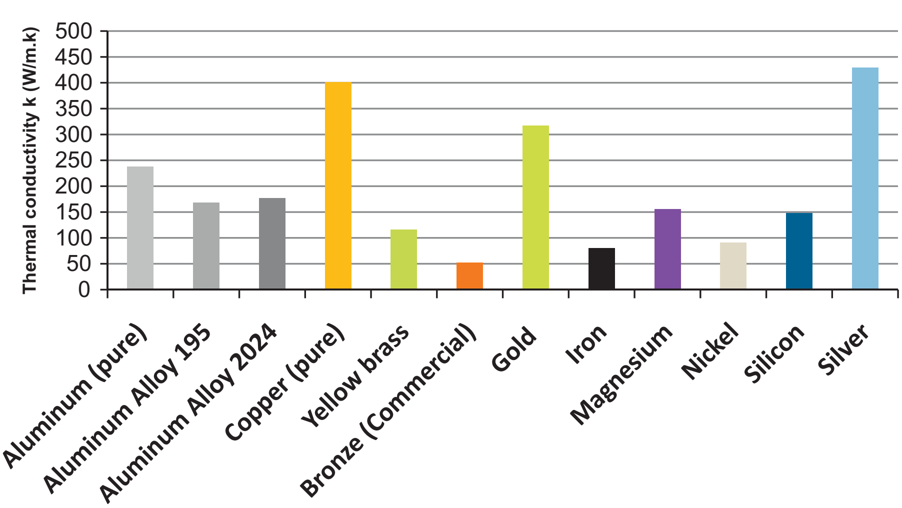

Fig. 2. Possible candidate's materials for microchannel heat sink fabrication (data from Ref. [2]).

Table 2
Specifications of the previously used coolants.

Gaseous coolants				Liquid coolants			
Air		N_2, He, NH_3 and others		Water		Nanofluids and others	
Advantage	Disadvantage	Advantage	Disadvantage	Advantage	Disadvantage	Advantage	Disadvantage
Availability	Poor heat transfer	Better heat transfer	Flammability Toxicity Corrosive Reactivity Cost	Better heat transfer	Leakage	Better heat transfer	Particle sedimentation Passage clogging
Stability				Availability	High power demands		High power demands

improve performance, different coolants were investigated under different flow conditions including natural and forced convection cooling modes, laminar and turbulent flows that were either developing or fully developed. Different results were obtained for different flow conditions and types.

Since the extensive literature review provided by Goodling and Knight [16], there have been only a few review studies available in the open literature associated with microchannel heat sink performance. These studies covered only certain aspects. For example, Morini et al. [17] review article which was dedicated to experimental studies and likewise Mohammed et al. [18] submitted a review that concentrated on experimental and theoretical studies conducted using nanofluids. In addition, previous review articles were organized using the classical form of review studies as each paragraph was dedicated to exploring a single study. This form requires a researcher to delve into the whole article to provide an even quick summary of the study. In this paper, a systematic review of the literature (see Table 3) is provided in a tabular form and it covers the different approaches used to analyze and optimize overall performance and the geometrical parameters of microchannel heat sinks with non-circular shapes. Table 3 can also be used as a benchmark reference to identify the coolant and materials used, flow types, optimization scheme employed and the final outcome of the studies. Furthermore, a comparative study, which highlighted the differences between the different aspects of previous studies along with their conclusions, is also discussed. Recommendations for future studies are also provided.

2. A general review

The performance of microchannel heat sinks with non-circular cross sections, particularly rectangular microchannel heat sinks, has been studied extensively. Different approaches, such as experimental [19], numerical [21] and analytical [22] and models including fin [30], porous medium [34] and thermal resistance [35] models have been used by different researchers to analyze and optimize the geometrical parameter combinations that have resulted in the best performances for microchannel heat sinks. Different coolants, materials, flow conditions and microchannel shapes were investigated to improve the heat removal capabilities of the microchannel heat sinks. The final outcomes of these studies were reported in different forms including graphical representations (plots) [36], numeric data [37] and empirical correlations [19].

The steps used to conduct the review in this study are depicted in Fig. 3. In the following section, the different aspects of previous studies were organized in a comparative study, or table form, to provide a general understanding of the development stages for microchannel heat sinks. The tabular form provides quick access to the information provided by these studies.

3. Comparative study

In this section, 69 selected articles dating from 1995 to 2013 that covered different experimental, analytical, and numerical studies were chosen to identify the different development stages and the methodologies employed for analyzing and optimizing the overall performance of microchannel heat sinks. Table 3 describes the aspects examined by researchers, which include the following:

3.1. Microchannel shapes

In an attempt to improve overall thermal performance, different microchannel geometries were used, such as rectangular, trapezoidal, triangular, circular, diamond and occasionally hexagonal shapes [24]. The primary motivation behind researcher's employment of different geometries was a need to increase the effective area available for heat transfer and reduce convective thermal resistance.

One of the most important goals of the majority of the studies was to lower total thermal resistance. Heat transfer augmenters such as ribs [47] and cavities [68] were used to increase surface area. Fig. 4 illustrates some of the heat transfer augmenters used in the different studies. Different path configurations, such as zigzags, curves, steps [63] and waves [64] within rectangular channel geometries were also attempted. The augmenters resulted in significant improvements in the overall thermal performance or lower thermal resistance. However, these improvements came at the expense of higher pumping power demands [64].

The dimensions of the microchannels ranged from 10 to 1500 μm. Despite the fact that the current review looked at non-circular geometries with a focus on rectangular shapes, the vast amount of studies that employed rectangular microchannel heat sinks revealed that it was the preferred choice (see Table 3) for researchers. This was likely due to the ease with which it can be machined, its stability [37] and its extremely high thermal performance [24].

3.2. The nature of the work

Different approaches and methodologies were utilized to investigate the overall performance of microchannel heat sinks. Experimental and analytical studies were conducted to explore the unknown aspects of different microchannel systems. The current review recorded that the experimental approaches were employed in the earlier stages (1995 to 2000) of the current field while with the

Table 3
Comparative study of the available literature on forced convection in microchannel heat sinks with two dimensional geometrical shapes.

Authors	Channel geometry	Nature of the work	Flow condition	Coolant types	Materials	Analysis methods	Optimization schemes	General outcome
Kleiner et al. [3]	Rectangular	Experimental Analytical	Laminar	Air	Copper Aluminum	Thermal resistance	Self-developing software	Plot
Peng et al. [19]	Rectangular	Experimental	Laminar Turbulent	Water Methanol	Stainless steel	–	–	Correlation
Harley et al. [4]	Rectangular Trapezoidal	Experimental Analytical	Laminar	Nitrogen Helium Argon	Silicon	–	–	Plot and numeric data
Peng and Peterson [20]	Rectangular	Experimental	Laminar Turbulent	Water	Stainless steel	–	–	Correlation
Choquette et al. [21]	Rectangular	Numerical Analytical	Laminar Turbulent	Water	Aluminum	Thermal resistance	Numerical	Plot
Zhimin and Fah [22]	Rectangular	Analytical	Laminar Turbulent	Water	Silicon	Thermal resistance	Self-developing software	Plot
Mala et al. [23]	Rectangular	Analytical	Laminar	Water	–	Mathematical model	–	Plot
Perret et al. [24]	Rectangular Hexagonal diamond	Analytical	Laminar	Water	Silicon	Thermal resistance	–	Numeric data
Tso and Mahulikar [25]	Rectangular	Analytical	Laminar Turbulent	Water	–	–	–	Correlation
Harms et al. [5]	Rectangular	Experimental	Laminar Turbulent	Deionized water	Silicon	–	–	Plot
Kim and Kim [6]	Rectangular	Analytical	Laminar	Water	Silicon	Porous medium	Numerical	Correlation
Rahman [26]	Rectangular	Experimental	Laminar Turbulent	Water	Silicon	–	–	Numeric data and plot
Fedorov and Viskanta [27]	Rectangular	Numerical	Laminar	Water	Silicon	3D Numerical	Numerical	Plot
Choi and Cho [7]	Rectangular	Experimental	Laminar Turbulent	Paraffin Water	Copper Silicon	–	–	Plot
Tunc and Bayazitoglu [28]	Rectangular	Numerical	Laminar Turbulent	–	–	Numerical	–	Numeric data and plot
Qu and Mudawar [8]	Rectangular	Numerical Experimental	Laminar	Deionized water	Oxygen free copper	3D Numerical	Numerical	Plot
Ryu et al. [29]	Rectangular	Numerical	Laminar	Water	Silicon	3D Numerical 2D Numerical	Numerical	Plot
Zhao and Lu [30]	Rectangular	Analytical Numerical	Laminar	Water	Copper Silicon	Porous medium Fin model	Numerical	Plot
Toh et al. [31]	Rectangular	Numerical	Laminar	Water	Silicon	3D Numerical	Numerical	Plot
Wu and Cheng [32]	Trapezoidal	Experimental	Laminar	Deionized water	Silicon	–	–	Numeric data
Tiselj et al. [33]	Triangular	Numerical Experimental.	Laminar	Water	Silicon	Numerical	Numerical	Plot
Kim [34]	Rectangular	Numerical Analytical	Laminar	–	–	Fin model Porous medium Numerical	–	Plot
Gamrat et al. [9]	Rectangular	Numerical	Laminar	Water	Bronze	3D Numerical 2D Numerical	Numerical	Plot
Liu and Garimella [35]	Rectangular	Numerical	Laminar	Water	Silicon	Thermal resistance Fin model Porous medium Fin–fluid coupled Numerical	–	Plot
Lee et al. [36]	Rectangular	Experimental Numerical	Laminar Turbulent	Deionized water	Copper Silicon	Numerical	–	Correlation and plot
Hetsroni et al. [37]	Rectangular Trapezoidal Triangular	Experimental	Laminar Turbulent	Water Deionized water	Copper Silicon	–	–	Plot
Kim and Kim [38]	Rectangular	Analytical Numerical	Laminar	–	–	Averaging model	Numerical	Plot
Li and Peterson [39]	Rectangular	Numerical	Laminar	Water	Silicon	3D Numerical model	Numerical	Numeric data and plot
Wang et al. [40]	Rectangular (tree-shape)	Numerical	Laminar	Water	Silicon	3D Numerical	SIMPLE Algorithm	Plot
Iyengar and Garimella [41]	Rectangular	Analytical	Laminar	Water Air	Copper	Thermal resistance model	–	Plot
Khan et al. [10]	Rectangular	Analytical	Laminar	Air	Silicon	Entropy generation minimization	Numerical	Numeric data and plot
Li et al. [42]	Rectangular	Numerical	Laminar	Water	Copper Silicon Stainless steel	3D Numerical	SAMPLER Algorithm	Plot

Table 3 (*continued*)

Authors	Channel geometry	Nature of the work	Flow condition	Coolant types	Materials	Analysis methods	Optimization schemes	General outcome
Chen [43]	Rectangular	Numerical Analytical	Laminar	–	–	Porous medium model	Finite difference method	Plot
Tsai and Chein [44]	Rectangular	Analytical	Laminar	Cu–water CNT–water	Silicon	Porous medium model	Numerical	Plot
Kou et al. [45]	Rectangular	Numerical	Laminar	Water	Silicon	Simulated annealing model	Numerical	Plot
Chen et al. [46]	Rectangular	Numerical	Laminar	Water	Silicon	Simulated annealing model	3D Numerical	Numeric data and plot
Husain and Kim [47]	Rectangular	Numerical	Laminar	Water	Silicon	Surrogate analysis methods	Evolutionary algorithm	Plot
Husain and Kim [48]	Rectangular	Numerical	Laminar	Water	Silicon	Surrogate analysis method	Hybrid evolutionary algorithm	Plot
Ighalo et al. [49]	Rectangular	Numerical	Laminar	Water	Silicon	3D Numerical	DYNAMIC-Q algorithm	Plot
Xie et al. [50]	Rectangular	Numerical	Laminar	Water	Copper	3D Numerical	Numerical	Numeric data and plot
Hu and Xu [51]	Rectangular	Numerical Analytical	Laminar	Water	Silicon	Thermal resistance	Sequential quadratic	Numeric data
Biswal et al. [52]	Rectangular	Analytical	Laminar	Water	Cu, Al, Si	Thermal resistance	–	Plot
Wang et al. [53]	Trapezoidal	Experimental Numerical	Laminar	Water	Silicon Pyrex glass	3D Numerical	–	Plot
Hong and Cheng [54]	Rectangular (Offset strip–fin)	Numerical	Laminar	Water	Silicon	3D Numerical	FLUENT	Plot
Husain and Kim [55]	Rectangular	Numerical	Laminar	Water	Silicon	Improved surrogate analysis	Evolutionary algorithm	Plot and numeric data
Deng et al. [56]	Rectangular	Analytical	Laminar	Water	Silicon	Improved porous medium	–	Plot
Kosar [57]	Rectangular	Numerical	Laminar	Water	Cu, Al, Si Steel, silica glass Quartz, polyimide	3D Numerical	–	Correlation and plot
Mohammed et al. [11]	Rectangular	Numerical	Laminar	Alumina–water	Aluminum	Numerical	Finite volume	Plot
Cho et al. [12]	Rectangular Trapezoidal	Experimental	–	R-123	Silicon	–	–	Plot
McHale and Garimella [58]	Trapezoidal	Numerical	Laminar	–	Silicon	3D Numerical	Finite volume	Correlation, plot and numeric data
Betz and Attingar[59]	Square	Experimental	Laminar (segmented flow)	Water	Polycarbonate–Al	–	–	Numeric data and plot
Zade et al. [60]	Rectangular	Numerical	Slip	Air	–	3D Numerical	–	Numeric data and plot
Chiu et al. [61]	Rectangular	Experimental Numerical	Laminar	Water	–	3D Numerical (CFD)	–	Plot
Chen and Ding [62]	Rectangular	Analytical	Laminar	Water Alumina–water	Copper	Porous medium	–	Plot
Moharana et al. [13]	Rectangular	Experimental Numerical	Laminar	Deionized water	Copper	3D Numerical (CFD)	–	Correlation and plot
Mohammed et al. [63]	Rect. (zigzag) Rect. (curve) Rect. (step)	Numerical	Laminar	Water	Aluminum	3D Numerical	Finite volume	Plot
Mohammed et al. [64]	Rect. (wavy)	Numerical	Laminar	Water	Aluminum	3D Numerical	Finite volume	Plot
Escher et al. [14]	Rectangular	Experimental Analytical	Laminar	SiO_2–water	Silicon	Thermal resistance model	–	Plot and numeric data
Ijam and Saidur [65]	Rectangular	Analytical	Turbulent	SiC–water TiO_2–water	Copper	Thermal resistance model	–	Plot
Mohammed et al. [15]	Triangular	Numerical	Laminar	Al_2O_3, Ag, CuO, diamond, SiO_2, TiO_2	Aluminum	3D Numerical	Finite volume	Plot
Mohammed et al. [66]	Trapezoidal	Numerical	Laminar	Diamond–water Diamond–EG Diamond–oil Diamond–glycerin	Copper Aluminum Steel Titanium	3D Numerical	Finite volume	Plot
Lelea [67]	Rectangular	Numerical	Laminar	Alumina–water	Copper	3D Numerical	Finite volume	Plot
Xia et al. [68]	Rectangular (triangular cavities)	Numerical	Laminar	Water	Silicon	3D Numerical	FLUENT	Plot
Saenen and Baelmans [69]	Rectangular	Numerical	Laminar	Air	Silicon	3D Numerical	SIMPLE algorithm	Plot
Ijam et al. [70]	Rectangular	Analytical	Laminar	Al_2O_3–water TiO_2–water	Copper	Thermal resistance model	–	Plot
Ahmed et al. [71]	Rectangular	Analytical	Laminar	Ammonia gas	Aluminum	Thermal resistance model	NSGA-II	Numeric data and plot
Sharma et al. [72]	Rectangular	Numerical	Turbulent (manifolds)	Hot water	Copper	3D Numerical	Ansys. CFX	Plot

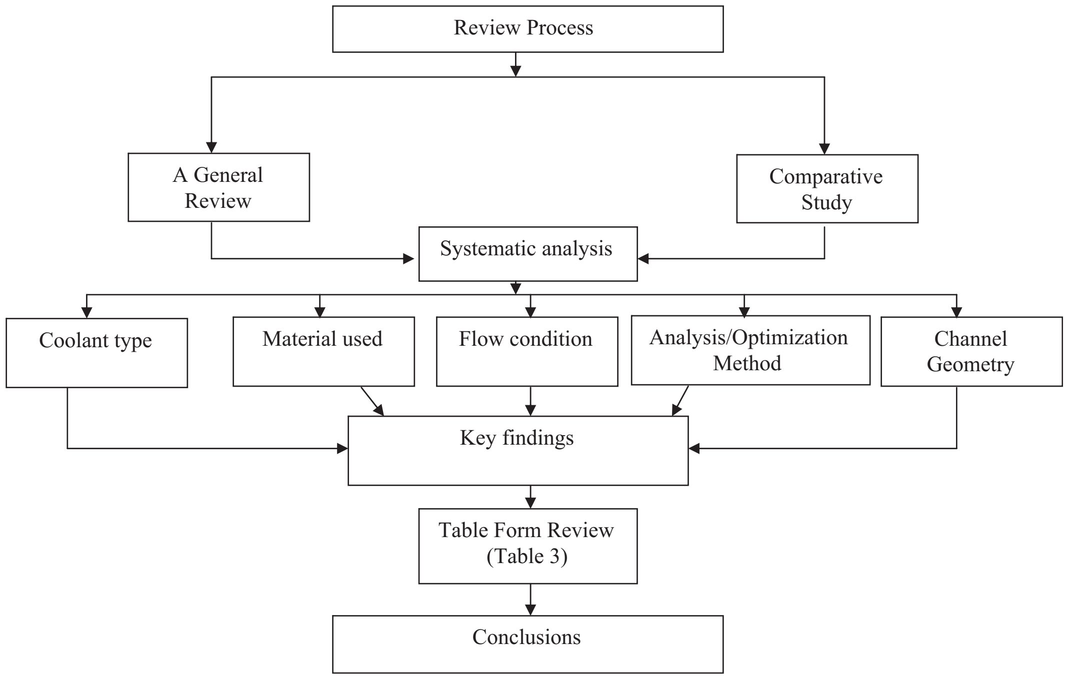

Fig. 3. Logical steps of the review process followed in the current study.

advances in the mathematical abilities, numerical [66] (two and three dimensional) and analytical [71] (e.g. evolutionary algorithms) were employed in the recent studies (2000 to present). The experimental studies were necessary to investigate the actual improvements in the performance of microchannel heat sinks to substantiate the claims made by any of the more recent numerical and analytical studies. Carrying out more experimental studies using nanofluids is an avenue that should be considered in future studies.

3.3. The flow conditions

The overall performance of microchannel heat sinks was examined under laminar and turbulent flow conditions. Some studies used both types of flow conditions [28]. Some studies employed turbulent flows in the feeding tubes (manifolds) and preserved laminar flows inside the microchannel heat sink [72].This review found that studies conducted using laminar flow conditions were the most common. Fig. 5 depicts the superiority of the studies that employed laminar flow over those that employed turbulent or laminar–turbulent flows. Their superiority was due to a general understanding that microchannel heat sinks perform better under laminar flows as their channels are short enough that turbulence could not develop. The range of laminar Reynolds number was between 100–2300. However, turbulent flows were considered in a number of studies. Some of the turbulent flow studies reported that microchannel heat sinks could provide a better performance under turbulent flow condition but, with higher pumping power demands.

3.4. The coolant employed

To accommodate the dramatic increase in the heat generated by modern electronics, different coolants were employed to dissipate the generated heat. Liquid coolants such as water, methanol [19], refrigerants [73] and recently nanofluids [66] were used in various microchannel heat sink systems while gaseous coolants such as air [3], helium, nitrogen, argon [4] and ammonia [71] were also utilized. Water and air were the most commonly used coolants due to their availability and associated low cost. Liquid coolants were proposed as an effective alternative for gaseous coolants as the later could not meet required cooling demands. Growing interest in employing nanofluids in microchannel heat sinks pointed out the fact that this particular aspect is still a very new area for most researchers.

3.5. The structural materials

The effect of different structural materials on overall thermal performance was investigated using different materials such as copper [3], aluminum [21] and silicon [22]. A few attempts were made to use other materials such as stainless steel [19], glass [57] and bronze [9]. The effect of different materials was more significant for larger channel heights and it became less significant when channel heights were smaller. This can be confirmed by the large number of microchannel heat sinks fabricated using silicon instead of copper or aluminum when the height of the microchannel is only a fraction of a millimeter. Using silicon results in a lighter heat sink which is compatible with current requirements.

3.6. The analysis methods

The use of different analysis methods is a crucial element in obtaining credible results. Models such as the fin model, the thermal resistance model, the porous medium model, and numerical analysis were among the models used by the researchers. The results obtained from these models were generally in close agreement with those obtained experimentally as well as with the results obtained using three-dimensional numerical simulations. Despite being a one dimensional model, the thermal resistance model was the most strongly recommend [35] due to its simple nature, accuracy, and flexibility. In some cases, the results from experimental studies were validated with results from a thermal resistance model [14]. Fig. 6 shows the validation process where both results exhibited a very good agreement. Failure of the fin model was reported by Qu and Mudawar [8] and Kim [34], and it was attributed to the wrong constant convective heat transfer

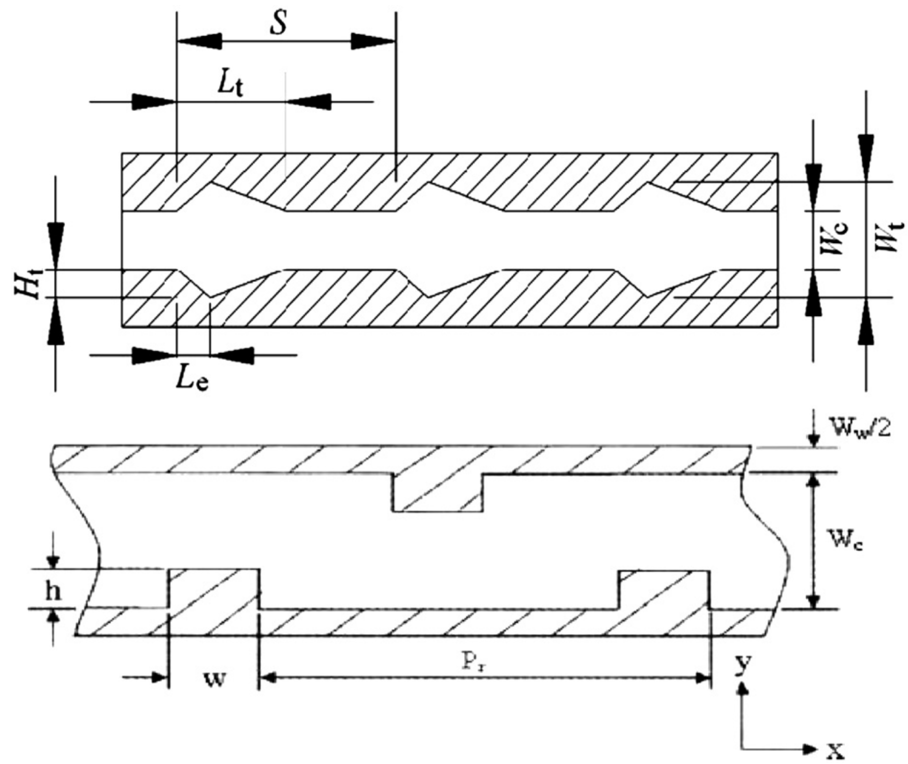

Fig. 4. Heat transfer augmenters used in the previous studies: (a) triangular cavities [68] and (b) rectangular ribs [47].

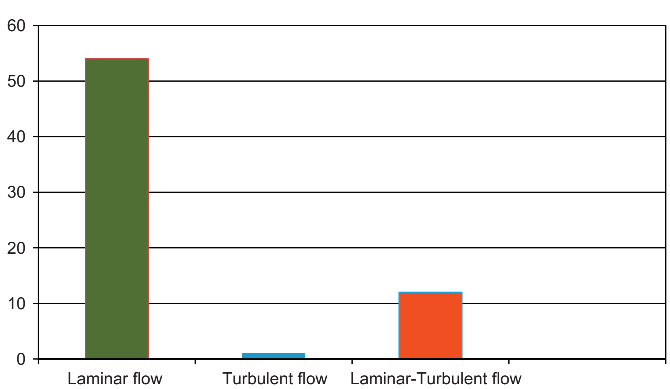

Fig. 5. Number of studies vs flow types.

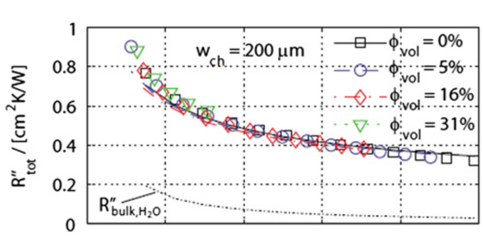

Fig. 6. Sample from the validation process between thermal resistance model and experimental study of Escher et al [14] (markers indicate experimental results and lines the theoretical predications (thermal resistance mode)).

coefficient, which resulted in an over prediction. The discrepancy was very obvious at very high channel aspect ratio values.

3.7. The optimization schemes

Many optimization schemes were employed by previous investigators in an attempt to obtain the optimum configuration for microchannel heat sinks. In the earlier stages of this field of study, numerical tools, such as the Lagrangian polynomial method, were the preferred option for most researchers [10]. Later, the field progressed with the introduction of evolutionary optimization algorithms. Single-objective and multi-objective algorithms, such as the Sequential Quadratic Programming Algorithm (SQP) [51] and the Non-Dominated Sorting Genetic Algorithm (NSGA-II) were used [71], provide an excellent level of performance. Many other algorithms, such as the Strength Pareto Evolutionary Algorithm (SPEA2), Multi-objective Genetic Algorithm (MOGA) and Goal Attainment Algorithm (GAA) are available. Their performance requires more investigations by researchers before they can be evaluated.

3.8. The final outcomes

Between 1995 and 2013 many studies have been carried out to analyze and optimize the overall performance of microchannel heat sinks. These studies are different in the way they present the final outcomes of their research. A common approach for reporting results is in the form of empirical correlations that look at the Nusselt number [57], numerical data for temperature and velocity profiles [60] and the graphs of optimized geometry as a function of thermal resistance and pumping power [71].

4. Conclusions

The problems of forced convection microchannel heat sinks have been extensively studied since their introduction by

Tuckerman and Pease [1]. Numerous experimental configurations and theoretical studies were devoted to investigate and ultimately improve the overall performance of microchannel heat sinks. Attempts at improvement included the use of different microchannel geometries, coolant types, and structural materials. Any improvements in the overall performance of the systems were analyzed using different analysis methods. The optimization of microchannel heat sinks was conducted using different optimization schemes. As a result, several conclusions can be drawn and they are summarized as follows:

i. The nature of the various studies can be divided into two main categories; the experimental and analytical period (1995 to 2000) and the numerical period (2001 to 2013). The experimental and analytical trend can be attributed to the lack of adequate information and data during this period. Between 1995 and 2000, the numerical approaches available at that time were very time consuming and there was not sufficient computing capabilities to efficiently describe events such as the non-continuum stages.
ii. The second period between 2001 and 2013 involved many numerical studies which were the result of the increasing availability of efficient numerical software. With the availability of data, researchers focused on using numerical methods in their approaches.
iii. Starting in 2008, researchers combined the strong capabilities of evolutionary algorithms in global searches with numerical approaches to develop new optimization schemes.
iv. Developments in the microfabrication techniques have driven designers to look into the use of different materials and shapes to improve the overall performance of microchannel heat sinks.
v. Researchers preferred laminar flows for their microchannel systems. New coolants with better heat removal capabilities, such as nanofluids, are the current interest of many researchers.
vi. Finally, the growing interest in the microchannel heat sinks, which is evident by the number of available studies, leads to the conclusion that research in this area is still developing.

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